UNDERSEA OPTICAL TRANSMISSION SYSTEM EMPLOYING RAMAN GAIN TO MITIGATE SHALLOW WATER REPAIR PENALTIES

Related Application

[0001] This application is a continuation-in-part of U.S. Application. Serial No. 10/313,965, filed December 6, 2002, entitled "Optical Transmission System Employing Erbium-doped Optical Amplifiers and Raman Amplifiers."

Field of the Invention

[0002] The present invention relates generally to optical transmission systems, and more particularly to an undersea optical transmission system that employs Raman amplifiers.

Background of the Invention

[0003] An undersea optical transmission system consists of land-based terminals interconnected by a cable that is installed on the ocean floor. The cable contains optical fibers that carry Dense Wavelength Division Multiplexed (DWDM) optical signals between the terminals. The land-based terminals contain power supplies for the undersea cable, transmission equipment to insert and remove DWDM signals from the fibers and associated monitoring and control equipment. Over long distances the strength and quality of a transmitted optical signal diminishes. Accordingly, repeaters are located along the cable, which contain optical amplifiers to provide amplification to the optical signals to overcome fiber loss. The optical amplifiers that are employed are generally erbium-doped fiber amplifiers. In some cases the optical amplifiers are Raman amplifiers that are used by themselves or in conjunction with erbium-doped fiber amplifiers. When erbium-doped fiber amplifiers are employed, the repeater spacing is typically in the range of about 50-80 km, so that the first repeater must be installed about 50-80 km from the shore.

[0004] The optical amplifiers are typically operated in a state of compression or gain saturation in which a decrease in optical input power is compensated by increased amplifier gain. That is, in compression the amplifiers regulate the optical power of the signals propagating through the optical fiber. A series of optical amplifiers extending

along a transmission path and operating in compression compensates for system degradations through a process of automatic gain adjustment. As a result, the optical output power from the amplifier remains at a substantially constant level even as the optical input power undergoes fluctuations. In other words, once the operating point (i.e., the point on the gain versus input power curve) of the optical amplifier has been determined, its output power will remain substantially constant, provided that the operating point corresponds to a state of compression or gain saturation. Accordingly, a decrease in the output power of a given EDF will not adversely affect overall system performance because the decrease will be compensated by a gain increase in subsequent downstream amplifiers.

[0005] A typical undersea route followed by an optical cable first traverses the relatively shallow continental shelf seafloor as it exits the transmitting terminal before entering deeper water. The cable once again traverses shallower water as it approaches the land-based receiving terminal. The repeaters located near the shore are generally buried in the seabed. Most cable failures arising in such transmission systems generally occur in the shallow portions of the seafloor as a result of fishing activity and impacts with anchors from ships. Such failures often require the replacement of damaged repeaters, which can be an unduly expensive and time-consuming proposition, particularly since they must be dug up from the seabed.

[0006] Copending U.S. Patent Appl. Serial No. 10/313,965 discloses an optical communication that employs both EDFAs and Raman amplifiers. The first and last transmission spans (i.e., the transmission spans nearest each of the land-based terminals) serve as the gain medium for the Raman amplifiers and the terminals themselves supply the pump energy. The remaining transmission spans are concatenated by EDFA-based repeaters. As a result of this arrangement the first and last transmission spans can be longer than the remaining EDFA-based transmission spans. As a result, the first and last EDFA-based repeaters may be located father from shore than would otherwise be possible if Raman gain were not employed. This increase in distance from the shore reduces the likelihood of damageto the first and last repeaters. By way of illustration, in some systems the first and last transmission spans may be about 125 km in length and the remaining spans may be about 70 km in length.

[0007] Undersea optical transmission systems must typically allow for the possibility

that over the system lifetime 1 cable repair will be necessary for every 20 km of transmission fiber located in shallow water. Moreover, each repair is anticipated to cause an increased optical loss of about 0.4 dB. Accordingly, in a conventional undersea transmission system that exclusively employs EDFAs, about 1.2 dB of loss can be expected for a shallow water transmission span 70 km in length. On the other hand, in the aforementioned undersea transmission system that employs Raman amplification in its first and last spans, which may be about 125 km in length, about 2.4 dB of loss can be expected.

[0008] While a 1.2 dB loss may be effectively overcome by the self-healing nature of the EDFAs, there is also a decrease in the optical signal to noise ratio (OSNR), which the EDFAs cannot repair.

[0009] Accordingly, there is a need to provide sufficient optical gain to the first and last spans of an undersea optical transmission system in the event of optical losses that reduce the optical signal power levels below that which can be adequately compensated by the EDFAs located in subsequent transmission spans.

Summary of the Invention

[0010] In accordance with the present invention, a method is provided for transmitting an information-bearing optical signal along an optical communication system. The communication system includes a transmitting terminal, a receiving terminal, and an optical transmission path optically coupling the transmitting and receiving terminals and having at least one rare-earth doped optical amplifier therein. The method begins by receiving the information-bearing optical signal from the transmitting terminal and supplying Raman gain to the optical signal in a first portion of the optical transmission path. Subsequently, the optical signal is forwarded to a first of the rare-earth doped optical amplifiers. After an increase in optical loss in the first portion of the optical transmission path arising from performance of a cable repair thereto, the Raman gain supplied to the optical signal is increased to overcome at least a portion of the increase in optical loss.

[0011] In accordance with one aspect of the invention, the information-bearing optical signal is received from the rare-earth doped optical amplifier, supplied with Raman gain, and forwarded to the receiving terminal.

[0012] In accordance with another aspect of the invention, the Raman gain that is supplied has a gain profile with a positive gain tilt over a signal waveband.

[0013] In accordance with another aspect of the invention, the rare-earth doped optical amplifier comprises a plurality of rare-earth doped optical amplifiers spaced apart from one another along the transmission path by a given distance. The given distance is less than a distance along the transmission path between the transmitting terminal and a length of the first portion of the transmission path in which Raman gain is provided.

[0014] In accordance with another aspect of the invention, the pump energy is supplied so that it is co-propagating with the signal.

[0015] In accordance with another aspect of the invention, the pump energy is supplied from the transmitting terminal.

[0016] In accordance with another aspect of the invention, the pump energy is supplied so that it is counter-propagating with the signal.

[0017] In accordance with another aspect of the invention, the counter-propagating pump is supplied from the receiving terminal.

Brief Description of the Invention

[0018] FIG. 1 shows a simplified block diagram of an exemplary wavelength division multiplexed (WDM) transmission system in accordance with the present invention.

[0019] FIG. 2 shows the relationship between the pump energy and the Raman gain for a silica fiber.

[0020] FIG. 3 shows a graph of the normalized gain of an erbium-doped optical amplifier as a function of input signal over a wavelength range of 1544 nm to 1560 nm.

[0021] FIG. 4 shows the spectral output from a typical Raman booster amplifier designed to have negative slope.

[0022] FIG. 5 shows the spectral output from the first erbium-doped optical amplifier, which has as its input the output signal from the Raman amplifier depicted in FIG. 4.

[0023] FIG. 6 shows the spectral output from the second erbium-doped optical amplifier, which has as its input the output signal from the first erbium-doped optical amplifier depicted in FIG. 5.

Detailed Description of the Invention

[0024] FIG. 1 shows a simplified block diagram of an exemplary wavelength division multiplexed (WDM) transmission system in accordance with the present invention. The transmission system serves to transmit a plurality of optical channels over a single path from a transmitting terminal to a remotely located receiving terminal. While FIG. 1 depicts a unidirectional transmission system, it should be noted that if a bi-directional communication system is to be employed, two distinct transmission paths are used to carry the bi-directional communication. The optical transmission system may be an undersea transmission system in which the terminals are located on shore and one or more repeaters may be located underwater

[0025] Transmitter terminal 100 is connected to an optical transmission medium 200, which is connected, in turn, to receiver terminal 300. Transmitter terminal 100 includes a series of encoders 110 and digital transmitters 120 connected to a wavelength division multiplexer 130. For each WDM channel, an encoder 110 is connected to a digital transmitter 120, which, in turn, is connected to the wavelength division multiplexer 130. In other words, wavelength division multiplexer 130 receives signals associated with multiple WDM channels, each of which has an associated digital transmitter 120 and encoder 110. Transmitter terminal 100 also includes a pump source 140 that supplies pump energy to the transmission medium 200 via a coupler 150. As discussed in more detail below, the pump energy serves to generate Raman gain in the transmission medium 200.

[0026] Digital transmitter 120 can be any type of system component that converts electrical signals to optical signals. For example, digital transmitter 120 can include an optical source such as a semiconductor laser or a light-emitting diode, which can be modulated directly by, for example, varying the injection current. WDM multiplexer 130 can be any type of device that combines signals from multiple WDM channels. For example, WDM multiplexer 130 can be a star coupler, a fiber Fabry-Perot filter, an in-line Bragg grating, a diffraction grating, cascaded filters and a wavelength grating router, among others.

[0027] Receiver terminal 300 includes a series of decoders 310, digital receivers 320

and a wavelength division demultiplexer 330. WDM demultiplexer 330 can be any type of device that separates signals from multiple WDM channels. For example, WDM demultiplexer 330 can be a star coupler, a fiber Fabry-Perot filter, an in-line Bragg grating, a diffraction grating, cascaded filters and a wavelength grating router, among others. Receiver terminal 300 also includes a pump source 340 that supplies pump energy to the transmission medium 200 via a coupler 350 to generate Raman gain.

[0028] Optical transmission medium 200 includes rare-earth doped optical amplifiers 210_1-210_n interconnected by transmission spans 240_1-240_{n+1} of optical fiber, for example. If a bi-directional communication system is to be employed, rare-earth doped optical amplifiers are provided in each transmission path. Moreover, in a bi-directional system each of the terminals 100 and 300 include a transmitter and a receiver. In a bi-directional undersea communication system a pair of rare-earth doped optical amplifiers supporting opposite-traveling signals is often housed in a single unit known as a repeater. While only four rare-earth optical amplifiers are depicted in FIG. 1 for clarity of discussion, it should be understood by those skilled in the art that the present invention finds application in transmission paths of all lengths having many additional (or fewer) sets of such amplifiers.

[0029] Transmission spans 240_1 and 240_{n+1} nearest terminals 100 and 300, respectively, serve as the gain medium for Raman amplifiers. In effect, transmission span 240_1 serves as a booster amplifier while the transmission span 240_{n+1} serves as a preamplifier to receiver terminal 300. The optical amplifiers 210_1-210_n, located between transmission spans 240_1 and 240_{n+1} along transmission medium 200, are rare-earth doped optical amplifiers such as erbium doped optical amplifiers. As previously mentioned, one important advantage arising from this arrangement is that the rare-earth doped optical amplifiers 210_1 and 210_n nearest terminals 100 and 300, respectively, can be located father from shore than would otherwise be possible if Raman gain were not supplied to transmission spans 240_1 and 240_{n+1}Since rare-earth doped optical amplifiers 210_1 and 210_n can be located farther offshore, fewer repeaters are required in the relatively shallow seafloor nearest the land-based terminals, which is the region in which the amplifiers are most likely to be damaged. Accordingly, system reliability can be significantly enhanced.

[0030] In some cases the distances between adjacent rare-earth doped optical

amplifiers 210_2-210_{n-1} are not constant. In these cases the respective distances between the rare-earth doped optical amplifiers 210_1 and 210_n and the terminals 100 and 300 may be greater than the average distance between adjacent rare-earth doped optical amplifiers 210_2-210_{n-1}. Alternatively, the distance between the rare-earth doped optical amplifiers 210_1 and 210_n and the terminals 100 and 300 may be greater than a majority of the individual distances between rare-earth doped optical amplifiers 210_2-210_{n-1}.

[0031] As previously mentioned, if there are cable cuts in either of the transmission spans near the shore (i.e., spans 240_1 and 240_{n+1}), the maximum total optical loss that may arise over the system lifetime is anticipated to be two or more times as great as in the corresponding transmission span of a system that exclusively employs EDFAs. While the self-healing nature of the EDFAs may be sufficient to restore the power level of the optical signals as a result of the cable cuts, the signal-to-noise ratio or fidelity of the optical signals may be degraded by an unduly large amount. Accordingly, in the present invention, because Raman gain is being supplied to these transmission spans by the transmitter and receiver terminals, the extra loss can be readily compensated by increasing the Raman pump power to thereby increase the Raman gain. In this way a satisfactory signal-to-noise ratio can be maintained.

[0032] Raman amplifiers use stimulated Raman scattering to amplify an incoming information-bearing optical signal. Stimulated Raman scattering occurs in silica fibers (and other materials) when an intense pump beam propagates through it. Stimulated Raman scattering is an inelastic scattering process in which an incident pump photon looses its energy to create another photon of reduced energy at a lower frequency. The remaining energy is absorbed by the fiber medium in the form of molecular vibrations (i.e., optical phonons). That is, pump energy of a given wavelength amplifies a signal at a longer wavelength. The relationship between the pump energy and the Raman gain for a silica fiber is shown in FIG. 2. The particular wavelength of the pump energy that is used in this example is denoted by reference numeral 1. As shown, the effective Raman gain occurs about 75 to 125 nm from the pump signal. The separation between the pump wavelength and the wavelength at which Raman gain is imparted is referred to as the Stokes shift. For silica fiber, the peak Stokes shift is about 100 nm.

[0033] By using multiple pump wavelengths the Raman amplifier can amplify a

relatively broad band of signal wavelengths. That is, varying the spectral shape of the pump energy can readily control the magnitude and gain shape of a Raman amplifier. For example, multiple pump wavelengths can be used to reduce gain variations over the signal bandwidth, thereby providing an amplifier with a flat gain shape. Alternatively, multiple pump wavelengths with a different spectral shape can be used to impart a gain tilt or slope to the signal bandwidth. If the gain increases with increasing signal wavelength the gain tilt is said to have a positive slope. If the gain decreases with increasing signal wavelength the gain tilt is said to have a negative slope.

[0034] As seen in FIG. 1, the pump source 140 supplying Raman gain to transmission span 240_1 is located in transmitter terminal 100 and thus the pump energy co-propagates with the signal. That is, the Raman booster amplifier is forward pumped. On the other hand, the pump source 340 supplying Raman gain to transmission span 210_{n+1} is located in receiver terminal 300 and thus the pump energy counter-propagates with the signal. That is, the Raman preamplifier is backward pumped.

[0035] The rare-earth doped optical amplifiers 210_1-210_n provide optical gain to overcome attenuation in the transmission path. Each rare-earth doped optical amplifier contains a length of doped fiber that provides a gain medium, an energy source that pumps the doped fiber to provide gain, and a means of coupling the pump energy into the doped fiber without interfering with the signal being amplified. The rare-earth element with which the fiber is doped is typically erbium. The gain tilt of an erbium-doped fiber amplifier is in large part determined by its gain level. FIG. 3 shows a graph of the normalized gain of an EDFA as a function of input signal over a wavelength range of 1544 nm to 1560 nm. At a relatively low gain (corresponding to a saturated EDFA), the gain tilt is positive, whereas at a high value of gain (corresponding to an unsaturated EDFA), the gain tilt is negative.

[0036] In optically amplified WDM communications systems, to achieve acceptable signal-to-noise ratios (SNR) for all WDM channels it is necessary to have a constant value of gain for all channel wavelengths. This is known as gain flatness and is defined as a low or zero value of the rate of change of gain with respect to wavelength at a fixed input level. Unequal gain distribution adversely affects the quality of the multiplexed optical signal, particularly in long-haul systems where insufficient gain leads to large signal-to-noise ratio degradations and too much gain can cause nonlinearity induced

penalties. Conventional erbium-doped optical amplifiers achieve gain flatness by careful design of the erbium doped fiber amplifiers and with the use of gain flattening filters.

[0037] One advantage arising from the use of a booster amplifier supplying gain to transmission span 240_1 is that gain flatness can be readily achieved. This is accomplished by selecting a gain shape for the booster amplifier that has a positive gain tilt. As previously mentioned, this can be accomplished in a well-known manner by selecting an appropriate spectral shape for the pump energy supplied to transmission span 240_1. On the other hand, the first erbium-doped optical amplifier 210_1 located downstream from the booster amplifier will have a negative gain tilt that can be used to counter-balance the positive gain tilt of the booster Raman amplifier to thereby provide an overall flat gain. The gain tilt of erbium doped optical amplifier 210_1 will be negative because the booster amplifier, operating in saturation, will not have sufficient gain to raise the signal level to the design point of the first erbium-doped optical amplifier. Since the input signal level to erbium-doped optical amplifier 210_1 is below its design point, the amplifier 210_2 will not be saturated. As discussed above in connection with FIG. 3, an unsaturated, high gain erbium-doped optical amplifier has a negative gain tilt. Moreover, as the signal continues to propagate along the transmission medium 200 subsequent erbium-doped optical amplifiers 210_2-210_n will restore the signal level to its design point as a result of the self-healing properties of such amplifiers. That is, the subsequent erbium-doped optical amplifiers will be operating in a state of gain saturation in which a decrease in optical input power is compensated by increased amplifier gain.

[0038] FIG. 4 shows the spectral output from a typical Raman booster amplifier designed to have negative slope so that when such a signal is subsequently inserted into an erbium-doped optical amplifier, the output is nearly at the design level and has minimal gain tilt. FIG. 5 shows the spectral output from the first erbium-doped optical amplifier and FIG. 6 shows the output from the second erbium-doped optical amplifier. Clearly the flat gain shape of the signals has been restored and the erbium-doped optical amplifiers quickly restore the signal level to its design point.

[0039] The gain shape of Raman preamplifier supplying gain to transmission span 210_{n+1} serving as a preamplifier is less important than the gain shape of the Raman booster amplifier because the preamplifier is located at the end of the system. Thus the

pump wavelengths and gain shape for the preamplifier should be selected to optimize the optical signal-to-noise ratio over the whole range of channel frequencies.

[0040] The Raman gain supplied by the Raman preamplifier is sufficient to compensate for a large portion of the excess loss in transmission span 240_{n+1} so that the signal arrives at the receiver terminal with all but possibly about 10 dB of design power. One advantage arising from the use of the Raman preamplifier is that its effective noise figure is much less than for erbium-doped optical amplifiers due to the distributed nature of the Raman amplification process. A shore-based counter-propagating pump at the receiver terminal 300 pumps the Raman amplifier 210_n. In this case, the Raman amplification process is less saturated than for the forward-pumped booster amplifier since the signal levels have dropped significantly by the time they reach the portion of the transmission fiber at the receiver end where the pump power is high. Therefore, high gains are achievable. In this case, the practical limit on Raman gain is constrained by double Rayleigh backscattering that causes high noise penalties for higher gains. Practically, the preamplifier can provide gains of 15-20 dB for 125-150 km spans, with very low effective noise figures.

[0041] Referring again to FIG. 1, an erbium-doped optical amplifier 360 is located in the receiver terminal between the coupler 350 that supplies the Raman pump energy and the WDM 330. The erbium-doped optical amplifier 360 supplies any additional gain needed by the signal before it traverses the relatively lossy WDM 330 to reach the receiver. Since the signal typically needs about 25-30 dB of net gain to counterbalance the loss in the transmission span 240_{n+1}, and the Raman preamplifier can only supply about 15 dB of gain, the erbium doped optical amplifier needs to supply about 10 dB of gain.

[0042] Although various embodiments are specifically illustrated and described herein, it will be appreciated that modifications and variations of the present invention are covered by the above teachings and are within the purview of the appended claims without departing from the spirit and intended scope of the invention. For example, while optical amplifiers 210_1-210_n depicted in FIG. 1 have been described as repeater-based rare-earth doped optical amplifiers, the present invention also encompasses repeater-based optical amplifiers 210_1-210_n of any type, including, but not limited to repeater-based Raman optical amplifiers.